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Executive Summary

Lake Thunderbird is a multi-purpose reservoir located in the Cross Timbers Ecoregion of south-central Oklahoma in Cleveland County. It serves as the terminal reservoir for a largely agricultural 256 square mile watershed. Constructed by the Bureau of Reclamation, Lake Thunderbird began operation in 1966. The lake boasts a large state park with many recreational opportunities including two marinas, multiple campgrounds with recreational vehicle sites, two swim beaches, multi-use trail systems, and a nature center. The lake itself is also a source of recreational activities, including a large boating presence, swimming, kayaking, jet skiing, and fishing. Under the authority of the Central Oklahoma Master Conservancy District (COMCD), Lake Thunderbird also serves as a major drinking water supply to three large metropolitan areas - Del City, Midwest City, and the City of Norman. COMCD has contracted with the Oklahoma Water Resources Board (OWRB) to monitor the lake for a variety of water quality parameters over the past twenty years. In 2020, monitoring was conducted to continue identification of any water quality concerns and an assessment of water quality standards. Assessment of the Supersaturated Dissolved Oxygen System (SDOX) efficacy was not part of 2020 monitoring and reporting as in years past.

In 2020, OWRB documented a typical thermal stratification pattern in the lake with the onset of stratification occurring in June and mixing in late September. The hypolimnion experienced anoxic conditions throughout the summer sampling season; the metalimnion also experienced anoxia from June to mid-September. While common in the hypolimnion, anoxia in the metalimnion highlights excessive algal growth and large oxygen demand of lake bottom sediments. Nutrient concentrations were high throughout the sampling season, reaching peak levels in late summer. Hypolimnetically stored nutrients also accumulated through the monitoring season because of sequestration below the density gradient, internal release from anoxic sediment, and organic material buildup. Riverine nutrient concentrations were higher than in lacustrine areas, likely due to stormwater inflows and wind mixing through these shallow areas that allow for continuous resuspension.

Chlorophyll, a measure of algal biomass, increased relative to previous monitoring years and remained excessive. In 2020, chlorophyll at Site 1 ranged from relatively low at 1.92 µg/L in April to the peak of 47.2 µg/L in late September. Taste and odor complaints collected by the City of Norman drinking water facility tallied 16 in 2019, but saw a 75 percent increase in 2020 to 28, 12 in July alone. Geosmin and 2-methylisoborneol (MIB), both algal compounds related to taste and odor problems, were also responsible for six complaints between November and December 2020, indicating active algal processes are occurring in winter.
Many stakeholders have a vested interest in Lake Thunderbird and its watershed, including the recently formed Lake Thunderbird Watershed Alliance. Efforts such as the Watershed Based Plan (WBP) (OCC, 2010), the Total Maximum Daily Load (TMDL) study (ODEQ, 2013), and COMCD’s support of in-lake management measures and continued water quality monitoring have been implemented for the lake. These plans and actions provide a foundation, which could be the impetus to mitigating poor water quality conditions in this critical waterbody. Additional investigative research is warranted to improve understanding of water quality issues and avenues of potential remediation.

In general, implementation of in-lake and watershed mitigation measures should be implemented in tandem to provide the greatest opportunity to improve water quality. Lake Thunderbird experienced prolonged periods of hypereutrophic conditions in 2020. Additionally, the lake fails to meet designated beneficial uses of Fish and Wildlife Propagation due to turbidity and dissolved oxygen, and Public and Private Water Supply from elevated levels of chlorophyll-a. A modernized comprehensive plan emphasizing both active in-lake and watershed best management practices could help Lake Thunderbird meet water quality standards for turbidity, dissolved oxygen, and chlorophyll-a. Continued exploration of other technologies for in-lake mitigation of water quality are critical to the success of improving water quality at Lake Thunderbird.
Introduction

Lake Thunderbird is a multi-purpose reservoir in the Cross Timbers Ecoregion of south-central Oklahoma in Cleveland County and has extensive history with water quality issues, documented in the long-term dataset from water quality monitoring conducted by OWRB. It continues to be listed as impaired in the latest approved Oklahoma Integrated Water Quality Report for the Public and Private Water Supply beneficial use due to exceedance of chlorophyll-a criterion, and the Fish and Wildlife Propagation beneficial use due to low dissolved oxygen conditions and increased turbidity (ODEQ, 2018). In response to these long-term water quality impairments, OWRB has provided water quality based environmental services for COMCD since 2000 and continues to conduct water quality monitoring at the lake and provide analysis on lake condition. This report presents data and analysis from the 2020 sample year.

In 2010, the COMCD gained funding to implement an in-lake mitigation infrastructure to address various aspects of impairment. An SDOX system was selected and began adding oxygen to the deepest portion of the lake’s anoxic hypolimnion near the dam while maintaining thermal stratification. This added oxygen was thought to limit the transfer of nutrients from the hypolimnion to surface waters and decrease the internal load of phosphorus, among other ancillary benefits. After years of operation, the system failed catastrophically in June of 2020 and is no longer operational. For additional information on the SDOX system, please refer to previous Thunderbird Water Quality Reports at www.owrb.ok.gov/reports and click on “Lake Restoration.” As such, assessment of the SDOX system is not included in this report.

Sampling Regime

In 2020, water quality sampling occurred from April 13 through October 14. Additional profiles and chlorophyll samples were collected at Sites 1 and 4 in November and December 2020, and January 2021, to aid in understanding winter algal activity after lake mixing. Monitoring was conducted for the parameters listed in Table 1 at the sites indicated in Figure 1. Sites 1, 2, and 4 represent the lacustrine, or open water zones of the lake where consistent summer stratification and an underlying hypolimnion are common features. Sites 6, 8 and 11 represent riverine zones of their respective tributaries. Finally, Sites 3 and 5 represent the transition zones between riverine and lacustrine portions of the lake. All zones of the lake are represented to allow for whole lake analysis, beneficial use assessment, and comparison between riverine and lacustrine zones.
Table 1. 2020 Water quality sampling parameters.

<table>
<thead>
<tr>
<th>SAMPLE VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Water Quality</strong></td>
</tr>
<tr>
<td>Chlorophyll-a</td>
</tr>
<tr>
<td><strong>Nutrients</strong></td>
</tr>
<tr>
<td>Total Kjeldahl Nitrogen (TKN)</td>
</tr>
<tr>
<td>Nitrate, as Nitrogen (NO₃⁻)</td>
</tr>
<tr>
<td><strong>Profile Parameters</strong></td>
</tr>
<tr>
<td>Dissolved Oxygen (DO) concentration</td>
</tr>
<tr>
<td>Specific Conductance (SpC)</td>
</tr>
<tr>
<td><strong>Environmental Observations</strong></td>
</tr>
<tr>
<td>Air Temp</td>
</tr>
<tr>
<td>Precipitation</td>
</tr>
<tr>
<td>Site Depth</td>
</tr>
</tbody>
</table>
Figure 1. 2020 Lake Thunderbird sampling sites. The lacustrine zone is comprised of Sites 1, 2, and 4. Riverine zones are represented at Sites 6, 8, and 11. Sites 3 and 5 represent the transitional zone from riverine to lacustrine.

Data for water quality indicators were collected following OWRB’s standard operating procedures (SOPs) for water quality samples (OWRB, 2018a). Variables such as pH, Dissolved Oxygen (DO), water temperature (°C), Specific Conductance (SpC), and Oxidation-Reduction Potential (ORP) were monitored in-situ utilizing a YSI® multi-parameter sonde. In accordance
with manufacturer’s specifications and published SOP’s, all parameters were calibrated weekly and verified daily with appropriate standards. Measurements were recorded at each sampling station on the lake in the form of a vertical profile. Readings begin 0.5 m below the surface of the water and continue in whole-meter intervals to lake bottom. During periods with anoxic conditions (DO < 2.0 mg/L), an additional reading is taken 0.5 m above the first depth with measured anoxia to narrow down the point of transition. A final reading is recorded 0.2 m above the lake bottom.

Water quality samples were collected utilizing a depth-integrated sampler (DIS) and churn splitter. A DIS is designed to collect a representative sample of the water column to a targeted depth, which is calculated by first measuring the Secchi disc depth (cm) at each site. The Secchi disc depth is doubled to represent the photic, or light penetrating zone of the water column and is the targeted DIS depth. For instance, if a Secchi disc depth is 80cm, the targeted depth for collecting a DIS is 160cm. The DIS is marked every 10cm from 50cm until 200cm. If the doubled Secchi disc depth is less than 50cm, a surface water grab is collected 0.5m below surface. More information on DIS procedures can be found in OWRB’s Standard Operating Procedure for the Collection of Water Quality Samples in Lakes (2019).

Other field observations such as Secchi disk depth, surface chlorophyll, and turbidity samples are collected at all sites. Nutrient samples are only collected at the surface of Sites 1, 6, 8, and 11. Additional sampling occurred at Site 1, including surface Total Organic Carbon (TOC) and at-depth nutrient samples collected with a Van Dorn sampler at 4.0m, 8.0m, 12.0m, and 0.2m above the bottom sediment-water interface. More information on Van Dorn sampling can be found in the SOP listed above. Sediment cores were also collected pre-and-post stratification to determine phosphorous release. Environmental conditions were also recorded for each site and can be found in Table 1 below. Nutrient analyses performed on these samples included both a phosphorus (P) and a nitrogen (N) nutrient series, as listed in Table 1.
Watershed

Lakes do not exist in isolation but interact as part of a complex ecosystem contained within a watershed. A watershed is the area of land that drains rainfall and streams to a “pour point,” which in Oklahoma is often a reservoir. Figure 2 presents Lake Thunderbird’s Hydrologic Unit Code 8 (HUC 8) watershed, encompassing 256 square miles in the Cross Timbers Ecoregion of central Oklahoma. Lake Stanley Draper lies within the same HUC 8 watershed, but their hydrologic connection to each other is negligible. Lake Stanley Draper is highly managed for Oklahoma City’s water supply and does not release downstream.

In 2015, the Bureau of Reclamation (BOR) conducted a bathymetric survey of the reservoir and calculated the top of the conservation pool at 1039.0 feet above sea level (Bureau of Reclamation, 2020). At this elevation, the lake surface area extends to 5,505 acres with a volumetric capacity of 103,840 acre-feet (Bureau of Reclamation, 2020). The BOR concluded that total volume of the lake has declined by 12% since construction in 1965, with an annual 50-year sedimentation rate of approximately 470 acre-feet per year (Bureau of Reclamation, 2020). Equating to an annual sediment yield, or amount of sediment entering the reservoir from the watershed, at around 1.93 acre-feet per square mile per year, which the Bureau considers high (Reclamation, 2006).

Lake Thunderbird is a Bureau of Reclamation multi-use reservoir. Major tributaries to the lake are the Little River to the west, Dave Blue Creek to the southwest, and Hog Creek to the north. The Little River serves as the longest flow path through the watershed, starting in the northwestern portion of the watershed and draining substantial amounts of the City of Moore before entering Lake Thunderbird near Site 6 (U.S. Geological Survey, 2021). Water is released below the dam into the Little River, which has a confluence with the Canadian River roughly 85 miles downstream.
Land uses in the watershed are important when determining potential sources of nutrients, sediment, or other forms of pollution. Table 2 presents land use in the Lake Thunderbird watershed. Grasslands and deciduous forest make up over 70 percent of land use and are the dominant categories while developed land makes up roughly 18% of the watershed. The majority of which is in the northwest portion and encompasses portions of Oklahoma City, Moore, and Norman. New land cover data collected in 2016 was made available for this report and the percent change column represents the increase (+) or decrease (-) from previous data collected in 2011.
Table 2. Land Use Acreage in Lake Thunderbird HUC 8 Watershed. (U.S. Geological Survey, 2021)

<table>
<thead>
<tr>
<th>Category</th>
<th>Acreage</th>
<th>Percent of Watershed</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open water</td>
<td>8,359</td>
<td>5.08%</td>
<td>+0.76%</td>
</tr>
<tr>
<td>Developed, open space</td>
<td>12,474</td>
<td>7.58%</td>
<td>-1.82%</td>
</tr>
<tr>
<td>Developed, low intensity</td>
<td>9,182</td>
<td>5.58%</td>
<td>+1.24%</td>
</tr>
<tr>
<td>Developed, medium intensity</td>
<td>6,080</td>
<td>3.70%</td>
<td>+1.71%</td>
</tr>
<tr>
<td>Developed, high intensity</td>
<td>1,376</td>
<td>0.84%</td>
<td>+0.41%</td>
</tr>
<tr>
<td>Barren Land</td>
<td>238</td>
<td>0.14%</td>
<td>+0.13%</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>61,607</td>
<td>37.45%</td>
<td>+2.16%</td>
</tr>
<tr>
<td>Evergreen Forest</td>
<td>322</td>
<td>0.20%</td>
<td>-0.03%</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>163</td>
<td>0.10%</td>
<td>-0.17%</td>
</tr>
<tr>
<td>Shrub Scrub</td>
<td>2842</td>
<td>1.73%</td>
<td>-0.01%</td>
</tr>
<tr>
<td>Grassland/Herbaceous</td>
<td>55,237</td>
<td>33.58%</td>
<td>-0.76%</td>
</tr>
<tr>
<td>Pasture/Hay</td>
<td>4,926</td>
<td>2.99%</td>
<td>-0.50%</td>
</tr>
<tr>
<td>Cultivated Crops</td>
<td>1,533</td>
<td>0.93%</td>
<td>-1.21%</td>
</tr>
<tr>
<td>Emergent Herbaceous wetlands</td>
<td>20</td>
<td>0.01%</td>
<td>+0.01%</td>
</tr>
<tr>
<td>Total Watershed</td>
<td>164,505</td>
<td>100%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Continuing development in the watershed underscores the need for Best Management Practices (BMPs) and opportunities for Low Impact Development (LID) measures that would support greater long-term watershed integrity.

**Climate**

Knowledge of potential climatological influences is critical when assessing the water quality of a waterbody. The hydrology and physical processes of a given reservoir significantly influence internal chemical and biological processes. For example, stormwater inflow influences nutrient content and composition, sediment loading, sediment suspension, and stratification patterns. In addition, changes in lake volume due to climactic events like rain or drought affect the extent of anoxia in the hypolimnion and alter oxidation-reduction potentials. Anoxia, in turn, influences chemical and biological processes.

**Figure 3** provides a graphical representation of Lake Thunderbird’s rainfall, elevation, inflow, and sampling dates for calendar year 2020. Annual precipitation at Lake Thunderbird dam in 2020 totaled 30.24 inches, as reported by the United States Army Corps of Engineers (USACE) (USACE, 2021), less than the lake’s long-term average of 38 inches (U.S. Geological Survey, 2021). Peak rainfall events correspond to increases in lake elevation. Inflow volumes were significantly lower in 2020 when compared to 2019, leading to the lake experiencing somewhat stable elevations throughout the year, with a low of 1037.76ft and high of 1039.41ft. This
becomes important when examining increasing nutrient levels and non-algal turbidity witnessed in the reservoir.

In addition to hydrology, air temperature can influence lake characteristics such as thermal stratification and nutrient availability, which subsequently influences primary productivity, which serves as proxy for algal growth or biomass. **Figure 4** compares monthly mean temperatures in 2020 to the long-term monthly mean using 2002-2020 data from the Oklahoma Mesonet’s Norman station, which is approximately 27 kilometers west of Site 1 at Max Westheimer Airport (Mesonet, 2021). For 2020, monthly mean temperatures were slightly lower than long-term averages, with five cooler than average months, including April-May and August-October. Peak air and water temperature again occurred in July, coinciding with the lake’s strongest stratification. Slight climatological variances from normal were observed in 2020, yet the lake’s typical pattern and duration of thermal stratification was maintained.
Figure 3. 2020 Inflow, Rainfall, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated.
A hydrologic budget, or water balance, is of considerable importance in water quality analyses and management. A general and simple hydrologic budget equation for a given waterbody can be defined by:

\[
\frac{\Delta V}{\Delta t} = Q_{\text{in}} - Q_{\text{out}} + PA_s - E_vA_s - W_s
\]

Where \( V \) is lake volume (acre-feet), 
\( A_s \) is lake surface area (acres), 
\( Q_{\text{in}} \) and \( Q_{\text{out}} \) are net flows into and out of the lake due to tributary inflows and gated releases, 
\( P \) is the rainfall directly on the lake (feet), 
\( E_v \) is the lake evaporation (feet), 
\( W_s \) is the water exported for water supply use (acre-feet).

In layperson terms, the rate of change in volume of water stored is equal to the rate of inflow from all sources, minus the rate of outflows. The input or inflows to a lake may include surface inflow, subsurface inflow, and water imported into the lake. The outputs may include surface

Figure 4. 2020 and Long-Term Average Monthly Temperature at the Norman Mesonet Station. (Mesonet, 2021)
evaporation and sub-surface outputs and water released downstream or exported as water supply from the lake. For Lake Thunderbird, subsurface and groundwater flow is assumed close to calculated error and insignificant, based on the relatively impermeable lake substrate.

The inputs to Lake Thunderbird include precipitation and inflow from the tributaries - encompassing all surface runoff in the basin. Because the USACE reported inflow term includes direct rainfall, we use their reported inflow minus calculated direct rainfall volume as the runoff term for the budget. Precipitation was calculated from the direct rainfall measurement data provided by the USACE. The precipitation contribution to the total inflows is derived by multiplying the daily rainfall amounts by the surface area of the lake on each date, as shown by:

\[ Q_p = P * A_s \]

Where \( Q_p \) is precipitation,
\( P \) is rainfall amount,
and \( A_s \) is the surface area of the lake.

Water outputs from Lake Thunderbird include gated dam releases, water supply withdrawals, and evaporation; USACE reports releases and withdrawals. Daily evaporation rates are calculated and reported by the USACE; their calculations relate solar radiation, wind speed, relative humidity, and average daily air temperature to estimate daily evaporation. The OWRB multiplies this rate by the daily average surface area of the lake to give the volume of water evaporated per unit time.

\[ Q_e = E_v * A_s \]

Where \( Q_e \) is evaporation,
\( E_v \) is the evaporation rate,
and \( A_s \) is the surface area of the lake.

The lake volumes, corrected to elevation, were calculated and the daily differences summed to account for the change in volume for each month. To estimate reservoir volume more accurately, the 2020 water budget used results from the BOR’s 2015 bathymetric survey elevation-capacity tables (Bureau of Reclamation, 2020).

A summary of monthly water budget calculations for Lake Thunderbird is below, where “Total Inputs” is the sum of all the flows into the lake and “Total Outputs” is the sum of all the outflows from the lake (Table 3). From Equation 2, the difference between the inputs and the outputs must be the same as the change in volume of the lake for an error free water budget so both input and output terms were calculated then compared. The difference between the inputs and outputs is in the I-O column and the monthly change in volume, calculated as the sum of daily volume
changes, is in ΔV column. Examination of the 2020 water budget shows nearly two-thirds of the total inputs to the lake occurred between January and June and is represented in peak inflow and elevation. **Figure 5** provides a visual summary of water gains and losses. Overall, inputs and outputs controlled an equal number of months, however, outputs in the latter half of the year came from water supply withdraw and evaporation rather than gated releases downstream. Inflows were highest in January, March (peak inflow), April and May and largely released downstream until June, where any subsequent inflow was held in the reservoir.

**Table 3. 2020 Lake Thunderbird Water Budget Calculations expressed in Acre-feet. Parentheses indicate a negative value. Values taken from USACE, 2021.**

<table>
<thead>
<tr>
<th>Month</th>
<th>Inputs</th>
<th>Outputs</th>
<th>Error Term</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inflow</td>
<td>Rainfall</td>
<td>Total Inputs</td>
</tr>
<tr>
<td>Jan</td>
<td>9,696</td>
<td>1,156</td>
<td><strong>10,852</strong></td>
</tr>
<tr>
<td>Feb</td>
<td>4,702</td>
<td>445</td>
<td><strong>5,147</strong></td>
</tr>
<tr>
<td>Mar</td>
<td>16,717</td>
<td>1,868</td>
<td><strong>18,585</strong></td>
</tr>
<tr>
<td>Apr</td>
<td>10,589</td>
<td>102</td>
<td><strong>10,691</strong></td>
</tr>
<tr>
<td>May</td>
<td>6,544</td>
<td>1,985</td>
<td><strong>8,529</strong></td>
</tr>
<tr>
<td>Jun</td>
<td>3,322</td>
<td>1,051</td>
<td><strong>4,374</strong></td>
</tr>
<tr>
<td>Jul</td>
<td>1,911</td>
<td>1,223</td>
<td><strong>3,134</strong></td>
</tr>
<tr>
<td>Aug</td>
<td>1,589</td>
<td>373</td>
<td><strong>1,924</strong></td>
</tr>
<tr>
<td>Sep</td>
<td>2,298</td>
<td>2,026</td>
<td><strong>4,324</strong></td>
</tr>
<tr>
<td>Oct</td>
<td>5,527</td>
<td>2,219</td>
<td><strong>7,745</strong></td>
</tr>
<tr>
<td>Nov</td>
<td>922</td>
<td>303</td>
<td><strong>1,230</strong></td>
</tr>
<tr>
<td>Dec</td>
<td>3,106</td>
<td>1,099</td>
<td><strong>4,205</strong></td>
</tr>
<tr>
<td>Total</td>
<td><strong>66,873</strong></td>
<td><strong>13,866</strong></td>
<td><strong>80,739</strong></td>
</tr>
</tbody>
</table>
Once a hydrologic budget is constructed, additional features of reservoir dynamics such as hydrologic retention time can be estimated. Tau (T), the hydrologic retention time, is the ratio of lake capacity at normal elevation to the annual exiting flow. This represents the theoretical time it takes a given molecule of water to flow through the reservoir. Lake Thunderbird’s water had a T value 1.90 years in 2020. Considerably lower than the average T (1995 to 2020) of 3.47 years. The lower value in 2020 may be attributed to the lowest volume of gated releases since 2017.

Total monthly error is the difference between the change in elevation-based lake volume and change in lake volume based on inputs-outputs. Utilizing 2015 BOR survey data, the 2020 cumulative annual error is 3,997 acre-feet, averaging to a monthly error slightly over 333 acre-feet. Without the updated bathymetry data, the annual error rate increases to 5,234 acre-feet or roughly 436 acre-feet per month. While seemingly negligible compared to overall reservoir volume, this demonstrates an increase in accuracy by reducing the number of unknowns.
According to the bathymetric survey completed by BOR in 2015, the average sedimentation rate below the spillway crest is approximately 428 acre-feet per year since impoundment 1965 (Bureau of Reclamation, 2020). This amount equates to roughly 11% of lost storage as original designed. The potential distribution of deposited sediment has consequences for in-lake processes such as sediment suspension and nutrient flux and is considered high (Reclamation, 2006).

Any groundwater loss and gain to the lake is assumed negligible for this analysis and any actual measurable changes are aggregated into the inflow variable. It is possible to verify the exchange of groundwater (loss or gain) with the lake by performing seasonal groundwater level surveys and reviewing the geology of the area. However, such a survey is a considerable undertaking and is beyond the scope of work for this project.

**Water Quality Evaluation**

**Thermal Stratification, Temperature, and Dissolved Oxygen**

Warming of the lake surface throughout spring marks the onset of thermal stratification, which occurs when an upper, less dense layer of water (epilimnion) forms over a cooler, denser layer (hypolimnion). The metalimnion, or thermocline, occurs between the epilimnion and hypolimnion and is the region with the greatest temperature and density gradient (Figure 6).
Stratification strengthens as the upper, epilimnetic waters warm throughout summer, while the hypolimnion stays cool. Because of these differences, thermal resistance to mixing prevents the epilimnion and hypolimnion from coming in contact during stratification. Thus, ongoing decomposition processes in the hypolimnion deplete dissolved oxygen and it is not replenished. The OWRB has documented this process at Lake Thunderbird each monitoring year since 2000. Stratification and hypolimnetic anoxia are inevitable and common processes across Oklahoma reservoirs, even without the extreme influence of outside forces.

Isopleths are a graphical method to illustrate lake dynamics as they interpolate hundreds of data points into one figure to show variation in measured parameters over depth and time. The isopleths of temperature and DO, while not exact, illustrate the process of thermal stratification and the impact of stratification on DO. Figure 7 displays all temperature and DO data from Site 1 over the monitoring period. Each line represents a specific temperature or DO value. More vertical lines indicate a completely mixed water column; when lines run horizontally, some degree of stratification is present. On the temperature plot, warmest temperatures are red, graduating to blue as temperature gets cooler, while on the DO plot, the lowest DO values are
colored red, graduating to purple at the highest DO. A few profiles of temperature and DO with respect to depth at Site 1 are included to highlight some elements of the sampling season and illustrate lake stratification layers (Figure 67). The remaining temperature and DO profile plots from Site 1 are contained in Appendix B.

Figure 7. 2020 Isopleths of Temperature (°C) and Dissolved Oxygen (mg/L) versus Depth (m) at Site 1.
Little thermal difference with depth was observed on the first sample date, April 13, 2020, indicating a well-mixed water column. By the second sample event on May 11, 2020, thermal stratification had slightly increased with only a 1.74°C temperature gradient from surface to bottom. By June of 2020, DO dynamics began setting up for the season with mostly anoxic hypolimnetic waters. As the season progressed, epilimnetic warming continued until reaching a peak temperature of 29.177°C on July 28, 2020 (Figure 8). Evident at this sampling event is the push of anoxic water upwards, creeping into the metalimnion and dominating the hypolimnion. This is evidence of increased organic load, and a high hypolimnetic water and sediment oxygen demand. Anoxic water in the metalimnion was observed throughout the lacustrine and transition zones during the summer and into September.

![Figure 8. A Temperature and Dissolved Oxygen vertical profile for Lake Thunderbird (July 28, 2020) highlighting a mostly anoxic metalimnion and anoxic hypolimnion.](image)
Epilimnetic water began to cool in September, deepening the epilimnion, although slight stratification persisted with some hypoxia in the hypolimnion. This marks the onset of lake mixing and by the October event, the water column was nearly isothermal (Figure 9).

![Figure 9. Temperature and Dissolved Oxygen profile at Site 1 for October 14, 2020 showing a nearly isothermal water column.](image)

Metalimnetic anoxia experienced throughout the lacustrine and transition zones on Lake Thunderbird in 2020 is indicative of a eutrophic system, driven by a high organic load created largely by algal growth and die-off. As algal cells die and settle out, hypolimnetic bacteria require an electron acceptor for survival and feed on the dead algae. When strong anaerobic conditions are present, elements other than oxygen function as terminal electron acceptors in the decomposition process, resulting in the release of nutrients and other constituents from the sediment. When mixing events occur, these released nutrients migrate to the surface waters where they can further stimulate algal growth.
Relative thermal resistance to mixing (RTR) calculations inform on the strength or intensity of stratification. This is a unit-less measure of temperature-based density differences, indicating how likely the layers are to mix. RTR calculations aid in determining the size of the epi-, meta- and hypolimnion layers and can be found in Appendix C.

**pH and Oxidation-Reduction (redox) Potential**

Lake Thunderbird exhibited increases in surface pH during the summer months indicating high rates of photosynthesis. High rates of photosynthesis will temporarily elevate pH as carbon dioxide is stripped from the epilimnion, while catabolism of the settling algae depresses pH in the hypolimnion (Figure 10). Sinking organic matter in summer months, due to high algal production or influx of organic material from the watershed, stimulates decomposition processes in the hypolimnion, driving pH and ORP down. In general, and as seen in 2020 data, peaks of high epilimnetic and low hypolimnetic pH correspond with peaks in algal productivity.

It is also important to note that, although not documented by our sampling regime, it is commonly accepted that epilimnetic pH has a daily variation of daylight elevation and nighttime lowering. Daily pH shifts follow oxygen concentration driven by algae, daytime photosynthesis, and nighttime respiration. In either case, carbon dioxide is either produced (respiration) or consumed (photosynthesis) faster than replaced via atmospheric diffusion. Without any impinging biological processes such as photosynthesis and respiration, baseline pH for Lake Thunderbird would be the common pH of bicarbonate buffered systems of 8.2.

![Figure 10. 2020 Isopleth of pH (S.U.) Versus Depth (m) at Site 1.](image-url)
In 2020, anoxia of the hypolimnion was not observed until the June sampling event (Figure 7), and by July, oxidation-reduction potential (ORP) dropped below 200 mV in anoxic conditions (Figure 11). Under oxygenated conditions, redox potentials remain highly positive (+300-500 mV) as oxygen is readily available as an electron acceptor during bacterial respiration. Normally, aerobic bacterial communities consume oxygen to the point of hypolimnetic anoxia, the bacterial community then shifts to an anaerobic one that uses nitrate as the final electron acceptor for respiration. During this bacterial community composition shift, the water maintains a relatively positive redox. Generally, as the ORP drops towards 100mV or lower (indicating strongly reducing conditions), sediment-bound phosphorus dissolves into the water column. The duration and extent of strong hypolimnetic reducing conditions are related to the accumulation of these compounds in the hypolimnion. Finally, low ORP conditions slow the oxidation (breakdown) of organic materials such as the contents of dead and dying algal cells providing another source of nutrients to accumulate in the hypolimnion.

**Figure 11.** 2020 Isopleth of Oxidation-Reduction Potential (mV) versus Depth (m) at Site 1.

**Nutrients**

High nitrogen and phosphorus loading, or nutrient pollution, has consistently ranked as one of the top causes of degradation in U.S. waters. In fact, lakes with excess nutrients are 2.5 times more likely to have poor biological health (EPA, 2009). Excess nitrogen and phosphorus lead to significant water quality problems including reduced spawning grounds and nursery habitats for fish species, hypoxic (<4.0 mg/L O₂) / anoxic (<2.0 mg/L O₂) conditions, fish kills, harmful algal blooms, taste and odor problems in finished drinking water, public health concerns related to recreation, and increased organic content of drinking water sources.
Dissolved nutrient concentrations consist of nutrients that are available for algal growth, such as ortho-phosphorus, ammonia, nitrate, and nitrite. High dissolved nutrient concentrations in the epilimnion generally indicate that nutrients are immediately available and therefore not limiting algal growth; while hypolimnetic concentrations are nutrients that could be available for future algal growth, especially during lake turnover in the fall. In general, when both nitrogen and phosphorus are readily available, neither is a limiting nutrient to algal growth, and excessive chlorophyll-a values can be expected. When high phosphorus concentrations are readily available in comparison to low nitrogen concentrations, algal growth may be nitrogen-limited and vice versa.

Site 1 is examined to represent lacustrine nutrient values; additionally, nutrient levels in riverine areas are also examined as nutrient levels vary spatially and seasonally. Nutrient graphs are presented here as a time series across three years to provide context across recent years.

**Phosphorus – P**

Total phosphorus (TP) is a measure comprised of particulate phosphorus and ortho-phosphorus and represents all phosphorus in the water sample. Ortho-phosphorus (ortho-P) is the bioavailable, dissolved form of phosphorus, used by algal communities for photosynthesis.

Epilimnetic TP was present in comparable levels to previous years through the beginning of the monitoring season before increasing in the late summer and fall. Values ranged from 0.0075 mg/L to a high of 0.069 mg/L in September. Predictably, epilimnetic ortho-P was below the laboratory reporting limit for much of the year, including the summer; this is the height of the growing season where algae will consume all ortho-P (Figure 12).
Figure 12. 2020 Surface Phosphorus variables as TP and Ortho-P (mg/L) at Site 1. Most Ortho-P values represent half the laboratory reporting limit of 0.0025 mg/L. Dashed lines represent detection limits for Total Phosphorus (brown) and Ortho-P (green).

Physical characteristics, such as stratification driven by thermal dynamics and DO depletion, influence numerous chemical and biological lake processes. Differences in water temperature and densities keep nutrients sequestered in the hypolimnion where they often accumulate through the season. Anoxic water and reducing conditions in the hypolimnion also create an environment favorable to sediment nutrient release. Hypolimnetic ortho-P accumulated throughout the stratification period, driving increased TP, before a decrease after lake mixing. (Figure 13).
Riverine sites are much shallower than lacustrine sites and therefore do not stratify as readily, allowing nutrients to continuously cycle through the water column for algal uptake. Wind mixing drives nutrient and sediment resuspension, throughout these shallow, turbid zones. Lacustrine and riverine sites’ nutrient concentrations are often distinct from each other; riverine values are consistently higher than in open water sites (Figure 12 and Figure 14). In 2020, Site 8 and 11 behaved similarly and exhibited TP values slightly higher than the lacustrine sites. Site 6, north of the Alameda Drive Bridge on the Little River arm, had the highest TP value at 0.186 mg/L in April. Peaking early, concentrations remained high all sampling season. The largest inflow of the
year was recorded in March and may have contributed to an early influx of phosphorus into the system (Figure 5).

![Riverine Phosphorus 2018-2020](image)

Figure 14. Surface Phosphorus (mg/L) from the three riverine sites, 2018-2020.

Site 1 surface TP and ortho-P values are consistent with those seen in eutrophic and hypereutrophic lakes and shows a slow increase over previous years, as indicated in Figure 12. Common in eutrophic systems, the buildup of hypolimnetic ortho-P is evidence of organic material settling from the epi- and metalimnion, in addition to active release from the anoxic sediment (Figure 13).

Riverine areas (Figure 14) are susceptible to wind mixing and resuspension of sediment and nutrients as they display greater impact from storm and high-flow events, likely driving the early peak in TP in Spring. Site 6 usually exhibits the highest phosphorus concentration, likely due to stormwater bringing in nutrients and sediment from the highly urbanized area upstream. These
higher levels of phosphorus represent a greater risk for elevated phosphorus in the main lake body, potentially leading to increased algal growth.

**Nitrogen – N**

Total nitrogen (TN) is a measure comprised of Kjeldahl nitrogen, nitrate (NO$_3$), and nitrite (NO$_2$), representing all organic and inorganic nitrogen compounds in each sample. Values at Site 1 ranged from 0.63 mg/L to 0.995 mg/L, increasing throughout the season and primarily driven by organic nitrogen present in algae (Figure 15). Of note is the gradual increase of TN over previous years.

![Total Nitrogen & Ammonia, 2018-2020](image)

*Figure 15. 2020 Surface Total Nitrogen (mg/L) over time at Site 1. Of note, samples in 2018 were processed by a lab with a lower Ammonia detection limit. 2019-present Ammonia samples are present below the detection limit of 0.1 mg/L and are graphed at half the detection limit (0.05).*

The typical pattern for Lake Thunderbird surface water has been seasonal increases of Kjeldahl nitrogen with ammonia, nitrate, and nitrite falling below reporting limit in subsequent order. In 2020, epilimnetic nitrate and nitrite fell below reporting limit in June and remained undetectable until briefly making an appearance at the September 16$^{th}$ sampling event (Figure 16). It again fell below reporting limit in late September before reappearing in October. This may correspond
with lake mixing in the Fall. Ammonia was not detectable at the surface throughout the season, likely due to ammonia being preferentially used by algae and thus follows quick depletion in a eutrophic to hypereutrophic reservoir.

Hypolimnetic total nitrogen peaked in September, coinciding with hypolimnetic ammonia accumulation. Examination of ammonia distribution with depth and over time showed a general increase of ammonia in the hypolimnion during summer months, when hypolimnetic waters were anoxic, followed by a sharp decrease below reporting limit in the fall (Figure 17).

Figure 16. 2018-2020 Surface Nitrate-Nitrite and Ammonia (mg/L) at Site 1. Of note, samples in 2018 were processed by a lab with a lower Ammonia reporting limit. 2019-present Ammonia samples are present below the reporting limit of 0.1 mg/L and are graphed at half the reporting limit (0.05 mg/L.).
Compared to the lacustrine zone, riverine total nitrogen levels were higher, suggesting the tributaries are an important source of nitrogen (Figure 18). Nitrogen in the riverine sites increased throughout the season and generally varied together, except for higher values observed in April at Site 6.

Lacustrine and riverine sites’ nutrient concentrations are often dissimilar from each other, as riverine values are consistently higher than those reported in open water sites. In 2020, Sites 8 and 11 behaved similarly and exhibited TN values slightly higher than the lacustrine sites. Nitrogen concentrations followed a similar peak and fall pattern at all riverine sites. Site 6 had the highest TN values lake-wide, peaking early in April at 1.3 mg/L.
Average Site 1 epilimnetic total nitrogen values were similar to previous years and are in the range of eutrophic reservoirs in Oklahoma. Epilimnetic ammonia was not detected throughout the monitoring season, in contrast to previous years. It is important to note that starting in 2019, the ammonia detection limit increased from 0.05mg/L to 0.1 mg/L with the implementation of a new reporting laboratory. However, this falls in line with biological principles as energetics of nitrogen assimilation by algae orders ammonia first; ammonia requires less energy for uptake, followed by nitrite, nitrate, and finally dinitrogen.

Hypolimnetic ammonia accumulated through the season, due to sequestration by the density gradient and release from lake-bottom sediments. The stepwise breakdown of thermal stratification in the fall mixed the nutrient rich hypolimnetic waters to the surface, decreasing the hypolimnetic concentration (Figure 19).
Riverine nitrogen concentrations peaked at the same time as lacustrine values and were measured as slightly higher than in lacustrine areas throughout the season. Site 6 exhibited the highest nitrogen values, likely attributed to storm water bringing nutrients into this shallow area of the lake.

In general, nutrients behaved similarly to previous years with riverine inorganic nutrients generally greater than lacustrine values, hypolimnetic accumulation of dissolved nutrients such as ortho-phosphorus and ammonia, and seasonal buildup of epilimnetic total phosphorus and nitrogen.
Algae

Chlorophyll-a is a pigment common to all photosynthetic plants and is used as a proxy for measuring algal biomass in aquatic ecosystems. Primary production is a term often associated with photosynthesizing organism, including algae. Algal biomass and subsequently biological production can have several impacts to overall water quality, including ecosystem stability, drinking water suitability, and recreational impacts related to water transparency. Increasing eutrophication in Oklahoma reservoirs has amplified the frequency and severity of blue-green algae blooms, which result in measurable amounts of cyanotoxins in affected waterbodies and can often lead to human health concerns and loss of recreational opportunities. Monitoring for blue-green algal blooms was not included in the scope of this project; however, the detection of taste and odor compounds, Geosmin and MIB, in recent years, confirms presence of nuisance blue-green populations in Lake Thunderbird.

Trophic state is a common designation used to classify lakes and reservoirs according to their level of productivity or algal biomass (Carlson, 1979). The process or rate at which lakes receive nutrients is known as eutrophy. Therefore, trophic state is a measure of a lake’s productivity. Recently, Lake Thunderbird’s classification has ranged from eutrophic to hypereutrophic, meaning it experiences high to excessively high algae growth. Characteristics of hypereutrophic systems include an anoxic hypolimnion, possible taste and odor issues in finished drinking water, and potential for algal scum and low transparency due to high algal biomass. These concepts will be explored in an upcoming section. Understanding and limiting the pathway for excessive nutrient loading is critical for effective water quality management and delivery of high-quality water.

Algal Biomass

Chlorophyll concentrations vary spatially and seasonally, and therefore, are presented as lacustrine and riverine sites over time. Lacustrine chlorophyll values began the monitoring season at relatively low levels, mostly lower than the 10 µg/L OWQS criterion until June when the lake began to stratify. Warmer epilimnetic waters and a greater amount of sunlight and nutrients lead to increased production of algae during summer months. This is a trend observed each year on Lake Thunderbird as well as others across Oklahoma. Chlorophyll values were relatively similar among lacustrine sites throughout the spring and early summer and all gradually increased (Figure 20). After the May 11 event, all lacustrine samples measured above OWQS until December. Interestingly, chlorophyll decreased across all sites in late summer (late August) before rebounding to their peak in September, corresponding with fall turnover.
Chlorophyll in riverine sites followed somewhat similar patterns as lacustrine, although at a higher magnitude (Figure 21). All sites started the season at or above the 10 µg/L criterion. Site 8 and Site 11 gradually increased over early summer while Site 6 increased sharply through July. Site 6 receives stormwater from the most urbanized portion of the watershed and may account for such sharp uptick. Peak chlorophyll values occurred in late July and began to subside through August and September before increasing a second time, likely due to influence from upland watershed dynamics. Nutrient availability is greater in riverine areas, providing algae more production potential. Inorganic turbidity is higher in these areas as well, due to inputs from the tributaries and watersheds, which likely suppresses algae from blooming to even higher levels.
Winter monitoring of chlorophyll at Site 1 and Site 4 was new in 2020 and allowed further understanding of winter dynamics. Profile and water samples were collected in November and December 2020 and January 2021. Results show a return of chlorophyll below the 10 µg/L criterion in December rebound to near or above criteria in January 2021 (Figure 22). This rebounding effect above OWQS indicates algal activity throughout winter month and may warrant additional monitoring.

Figure 21. 2020 Lake Thunderbird surface chlorophyll (µg/L) at riverine sites. Bottom dashed red line indicates SWS criteria of 10 µg/L. Top dashed line represents values corresponding with a hypereutrophic reservoir.
Figure 22. Chlorophyll dynamics throughout the year at Sites 1 & 4. Bottom dashed red line indicates SWS criteria of 10 µg/L. Top dashed line represents values corresponding with a hypereutrophic reservoir. Chlorophyll sampling in November-January 2021 were new in 2020.

Algal Limitation

Understanding causal factors of excessive algae growth is critical in developing effective mitigation measures. To this end, the OWRB has employed a variety of diagnostic tools to examine the relationship between algal macronutrients (light, phosphorus, and nitrogen) and measures of algal biomass.
**Nutrients**

Phosphorus is desirable as the limiting nutrient for most freshwater systems because under phosphorus limiting conditions, green algae will typically be the predominant algal community. This is opposed to a blue-green algae predominance, which, while less common, can cause a multitude of issues ranging from human health and recreation, to drinking water supply, and fish community structure. A common tool for examining the limiting nutrient relationship is the ratio of Total Nitrogen to Total Phosphorus (TN:TP).

TN:TP ratios are used to predict whether nitrogen or phosphorus is the most likely nutrient to limit algal growth. Dzialowski *et al.* (2005) has divided the molecular ratio of total nitrogen to total phosphorus into three ranges, wherein a TN:TP ratio of less than or equal to 18 indicates a nitrogen-limited waterbody, ratios of 20-46 indicate a co-limitation of nitrogen and phosphorus, and waters having ratios greater than 65 are regarded as phosphorus-limited. In most eutrophic Oklahoma reservoirs, a co-limitation prediction turns out to be no chemical nutrient limitation, because both nutrients are readily available in significant amounts and produce high algal productivity.

Historically, Lake Thunderbird has been in the co-limitation range with both nutrients readily available for algal growth. However, 2020 data shows much of the lake was in the indeterminate zone for much of the year, including the growing season (Figure 23).
Turbidity and Secchi disk depth are ways of measuring water clarity and amount of suspended particles in a lake. In pristine and natural lakes, Secchi disc depths can measure in several meters. However, in most Oklahoma lakes, it is common for Secchi depth to be less than one meter. Secchi disk depth can provide information on light’s ability to penetrate and influence the water’s productivity.

In 2020, Lake Thunderbird’s non-algal turbidity was calculated to examine its effect on algal limitation using the equation below, derived from BATHTUB model (Walker, 1999). Non-algal turbidity generally describes turbidity associated with material originating elsewhere and was brought in or introduced to the system. This material is often referred to as allochthonous in geology.
Eq. 5 \[ T = \frac{1}{SD} - 0.025 \text{Chl a} \]

Where SD is Secchi Depth in meters

and Chl a is extracted chlorophyll a result value in mg/L.

Of the samples analyzed for non-algal turbidity (T) influence on algal growth, 61 percent were found to have a T value greater than one, indicating allochthonous particulates are potentially important and the expected algal response to nutrients is likely low. Meaning turbidity from particles brought into the system is potentially more important in limiting light’s ability to drive excessive algal growth, regardless of excessive nutrients in the system.

Five instances in the lacustrine portion of the reservoir had T values below 0.4, which indicates turbidity from allochthonous particles are unimportant and high algal response to nutrients is expected. This follows as the lacustrine portion of Lake Thunderbird traditionally has greater secchi disk depths than riverine portions. Despite the presence of high nutrient concentrations, chlorophyll values were lower than would be expected due to turbidity from non-native particles.

**Trophic State Index – TSI**

A common method of classifying lakes based on biological response to nutrients is trophic state, which indicates the amount of biological activity sustained in a waterbody at a particular time. Lakes that have high nutrient concentrations and productive plant growth are described as eutrophic, whereas low nutrient concentrations and low plant growth lakes are characterized oligotrophic (Water on the Web, 2004). Lakes that exhibit moderate levels of nutrients and plant growth are termed mesotrophic. Carlson (1977) developed the most widely used biomass based Trophic Status Index (TSI) to classify and describe lakes. The Carlson chlorophyll TSI metric has long been used by OWRB to determine lake trophic status. **Table 4** below presents the various trophic states and associated descriptions.

<table>
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<tr>
<th>Trophic State</th>
<th>TSI Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>Oligotrophic</td>
<td>&lt; 40</td>
<td>Low primary productivity and/or low nutrient levels</td>
</tr>
<tr>
<td>Mesotrophic</td>
<td>41-50</td>
<td>Moderate primary productivity with moderate nutrient levels</td>
</tr>
<tr>
<td>Eutrophic</td>
<td>51-60</td>
<td>High primary productivity and nutrient rich</td>
</tr>
<tr>
<td>Hypereutrophic</td>
<td>&gt; 60</td>
<td>Excessive primary productivity and excessive nutrients</td>
</tr>
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</table>

This concept has been expanded over time to classify each lake into a particular trophic state based on a series of metrics. These metrics in turn are used to assess biological processes and
water quality trends; comparing each metric can shed light on what drives algal growth. Chlorophyll is the most relatable TSI metric, as it is the most direct measure of algal biomass, which is the measure of primary productivity that the trophic state seeks to classify. Figure 24 displays Lake Thunderbird’s TSI (Chl-a) levels at Site 1, beginning the season as oligotrophic and ran the full gamut of trophic statuses, quickly accelerating to hypereutrophic by July and remained into November.

![Chl-a TSI, 2020](image)

*Figure 24. Site 1 Chlorophyll TSI in 2020. Dashed lines represent the divisions of trophic states.*

The advancement of lakes toward a eutrophic or hypereutrophic condition is often accelerated by anthropogenic activities that introduce excess nitrogen and phosphorus into lakes. This is commonly referred to as cultural eutrophication.

In a similar pattern as Site 1, TSI (Chl-a) at the riverine sites increased throughout the season and were mostly in the eutrophic and hypereutrophic ranges. Chlorophyll TSI varied between individual sites and were consistent with measured chlorophyll in the system. Figure 25 displays riverine TSI throughout the 2020 sample year.
Total Organic Carbon – TOC

Total organic carbon (TOC) is a measure of carbon containing compounds present in a water sample, allowing insight to the amount of organic material present. Sources of these organic compounds include soil and plant detritus and to a lesser degree, even carbon present in living material such as bacteria and plankton (Wetzel, 2001). Wetzel presents median organic carbon content for eutrophic lakes as 12.0 mg/L, oligotrophic lakes as 2.2 mg/L, and rivers as 7.0 mg/L (2001). In 2020, Lake Thunderbird surface TOC values at Site 1 ranged from 5.07 to 6.79 mg/L with a mean value of 5.81 mg/L (Table 5). TOC is an especially important measure for water treatment plants to inform on potential creation of Disinfection By-Products (DBPs). Chlorine compounds used in disinfection can react with organic matter to creating by-products that could be carcinogenic (TCEQ, 2002). Reducing TOC in the source water could lead to a reduction in treatment cost for finished drinking water.
Table 5. 2020 Lake Thunderbird Total Organic Carbon (mg/L).

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<tr>
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Taste and Odor Complaints

The City of Norman has provided data on the number of taste and odor complaints for the period of record (2000 – 2020) and more recently included taste and odor compound analysis. Annual data has indicated that changes in lake water quality correlates with customer complaints in the final finished drinking water. Consumers at the tap can detect taste and odor causing compounds in extremely low concentrations (~ 5 ng/L) (Graham et al 2008). Algae produce the majority of taste and odor compounds (T&O) found in Oklahoma reservoirs. The most common drinking water T&O that are problematic are Geosmin and 2-methylisoborneol (MIB). Both of which are produced primarily by Cyanobacteria.

Taste and odor complaints in 2020 exhibited a different pattern from previous years, with relatively few until July, when 12 grievances were registered (Figure 26). In past years T&O complaints coincided with lake mixing events, cycling hypolimnetic chemicals into the water column. However, in 2020, Geosmin did not peak until November, while MIB spiked in late August (Figure 27). Overall measured annual averages for both parameters where lower than 2019. Additional sampling events were conducted throughout the winter at Sites 1 and 4 to better understand algal and chlorophyll dynamics. Results from October 2020 through January 2021 indicate chlorophyll fell below or near the OWQS threshold of 10 µg/L.
Figure 26. 2018-2020 City of Norman compiled monthly Taste and Odor complaints. Data is from personal communication with R. Croft, City of Norman, March 25, 2021.
Figure 27. 2020 City of Norman monthly raw water laboratory analysis for MIB and Geosmin. MIB was less than 2.0 ng/L (nanograms/Liter or parts per trillion) March-May and again October-December. Geosmin and MIB were not evaluated in September. Data is from personal communication with R. Croft, City of Norman, March 25, 2021.

Water Quality Standards

All Oklahoma surface waters are subject to Oklahoma’s Water Quality Standards (OAC 785:45) and Implementation Rules (OAC 785:46), designed to maintain and protect the quality of waters of the state. Oklahoma Water Quality Standards (OWQS) are rules adopted by Oklahoma in accordance with the federal Clean Water Act, applicable federal regulations, and state pollution control and administrative procedure statutes. Identification and protection of beneficial uses are vital to water quality standards implementation. Beneficial use designations for Lake Thunderbird are Public and Private Water Supply (PPWS), Fish and Wildlife Propagation (FWP), Agriculture, Recreation, and Aesthetics.
Lake Thunderbird is listed in the latest approved Oklahoma Integrated Water Quality Report as impaired due to low dissolved oxygen, excessive turbidity, and excessive chlorophyll (ODEQ, 2018). In order to address these impairments, Lake Thunderbird has undergone Total Maximum Daily Load (TMDL) development by the ODEQ with the resultant report approved by the Environmental Protection Agency (EPA) in 2013. The TMDL analysis requires a 35% long-term average load reduction of total nitrogen, total phosphorus, and total suspended solids from the 2008-2009 watershed load estimates in order to restore the lake’s beneficial uses. Implementation of the TMDL is underway and point source and non-point source measures are outlined in the Final TMDL Report (Dynamic Solutions, 2013).

The Oklahoma Water Quality Standards Implementation Rules contain Use Support Assessment Protocols (USAP) for Oklahoma waterbodies. This USAP is the statewide methodology for integrated report water quality assessments (i.e., 305(b) and 303(d) reports). The 2020 water quality data was assessed in accordance with the USAP to evaluate current conditions relative to OWQS attainment or nonattainment. Physical, chemical, and biological data on Lake Thunderbird were used to assess the lake condition and determine if lake water quality supports its designated beneficial uses and are outlined below.

**Dissolved Oxygen – DO**

Dissolved oxygen criteria are designed to protect the diverse aquatic communities found throughout Oklahoma waterbodies. For warm water aquatic communities, such as Lake Thunderbird, two assessment methodologies apply to protect Fish and Wildlife Propagation beneficial use: surface and water-column/volumetric (OAC 785:46-15-5). Surface water DO criteria for not supporting is a seasonal threshold of 4.0 mg/L during the summer months and 5.0 mg/L in spring and fall. Accordingly, no surface DO readings fell below either thresholds for not supporting in 2020.

Volumetric criteria for fully supporting the Fish and Wildlife Propagation beneficial use has a threshold of less than 50% of the cumulative lake volume measuring anoxic (< 2 mg/L DO). 2020 proved to be a favorable year for dissolved oxygen at Lake Thunderbird with no months exceeding the 50% lake volume criteria. Average percent of oxygenated lake volume between April and December 2020 was over 88%. However, previous reports for 2018 and 2019 sample years highlight occurrences of the lake failing to meet volumetric criteria.
**Chlorophyll-a**

Oklahoma surface water drinking supplies are vulnerable to eutrophication and communities can experience substantial hardship and excessive costs to treat water affected by eutrophication. Specifically, blue-green algae (cyanobacteria) blooms are considered a principal source of compounds that cause T&O complaints. Blue-green algae also produce several toxic and carcinogenic compounds such as microcystin – a known hepatotoxin that can cause liver damage. The OWQS have provided additional protections from new point sources and protection against additional loading from existing point sources by identifying these at-risk reservoirs as Sensitive Water Supplies (SWS). Lake Thunderbird has this SWS designation and as such, is required not to exceed the long-term average chlorophyll concentration of 10 µg/L at a depth of 0.5 meters. In 2020, the lake wide chlorophyll average in Lake Thunderbird was 30.75 µg/L, with over 84% of samples exceeding 10 µg/L, whereas samples collected in 2019 had a lake wide average of 24.3 µg/L, with 75% of samples exceeding (Figure 28). The long-term ten-year lake-wide average is 26.0 µg/L, with 82% of samples exceeding 10 µg/L. Based on these calculations, Lake Thunderbird’s beneficial use of Public and Private Water Supply would be considered as non-supporting and impaired with respect to chlorophyll.
Figure 28. 2020 Lake Thunderbird chlorophyll-a (µg/L) by site. Boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values.

**Water Clarity**

Turbidity and Secchi disk depth are methods of measuring water clarity and the amount of suspended particles in a lake. Typical Secchi disk depths of eutrophic Oklahoma reservoirs measure one meter or less. In Lake Thunderbird, 2020 secchi disk depths ranged 5 centimeters (cm) at Site 6 to 125 cm at Site 1. Whole lake average of Secchi depth was 48.76 cm, a slight improvement from 2019’s average of 49.01 cm. The lacustrine sites had the deepest Secchi depths while the riverine sites had the shallowest, as is typical of Oklahoma reservoirs (Figure 29).
Figure 29. 2020 Lake Thunderbird Secchi Disk Depth (cm) by site. Boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Depth starts at 0 to represent the surface of the water.

The OWQS criterion for turbidity for the protection of the Fish and Wildlife Propagation beneficial use, is 25 Nephelometric Turbidity Units (NTU). If at least 10% of collected samples exceed this value in the most recent 10-year dataset, the lake is not supporting its beneficial use, and is thus impaired for turbidity. For the 2020 sampling season, the lake wide turbidity average in Lake Thunderbird was 20.01 NTU, with 26.3% of the samples exceeding 25 NTU, all of which were in the riverine portions of the lake (Figure 30). The long-term, ten-year, lake-wide average is 24.4 NTU, with 26.5% of those samples exceeding 25 NTU. Based on these calculations, Lake Thunderbird is not supporting for the Fish and Wildlife Propagation beneficial use with respect to turbidity.
Discussion

Since 2000, OWRB has monitored the water quality of Lake Thunderbird and documented the continued degradation of water quality from cultural eutrophication. As time passes, impacts become increasingly severe. From rapid urban development in the watershed to excessive levels of nitrogen and phosphorus—especially in riverine areas, to progressively higher levels of measurable chlorophyll. All of which contribute and culminate in the loss of beneficial uses.

Climactically, Lake Thunderbird experienced a slightly cooler April-May and August-October than average in 2020. Epilimnetic water temperature peaked in early June. Water level, in terms of elevation, remained rather stable the entire year. Maximum elevation was observed in June and was below normal elevation the remainder of the year. The overall pattern of stratification remained comparable to previous years. Thermal stratification began to set up by the May sampling event, coinciding with a small anoxic volume in the hypolimnion. Indicative of a hypereutrophic system, anoxia was creeping into the metalimnion by July and persisted through the summer until thermal mixing in late September. This recent trend of metalimnetic anoxia...
underscores the excessive algal growth and high sediment oxygen demand and the need for addressing the water quality impairments in the lake. Reducing conditions in the hypolimnion, indicated by low ORP values, occurred from July to September and encompassed a large volume of water, slowing the breakdown of organic materials. This provides a larger amount of material mixed into the surface water following the disruption of thermal stratification.

Dissolved and total forms of nutrients, primarily nitrogen and phosphorus, were examined with respect to their spatial and temporal trends, as well as their role in limiting algal growth. Total phosphorus values were consistent with those typically reported in Lake Thunderbird during recent years but are higher than optimum to effectively curb excess biological productivity. Late summer and early fall hypolimnetic phosphorus values were high, stemming from the effect of thermal stratification and internal release from anoxic sediment. In fall, hypolimnetically stored nutrients mixed into the water column resulting in higher epilimnetic values. Ortho-P, the biologically available form of phosphorus, was not detectable in the epilimnion, likely due to uptake by algae. Hypolimnetic ortho-P accumulated throughout the season before mixing into the water column in the fall. Lacustrine phosphorus concentrations were generally lower than riverine surface phosphorus, suggesting substantial loading of phosphorous is entering the system as runoff from the watershed. Riverine areas also allow constant cycling and resuspension of nutrients due to their shallow depths and susceptibility to wind mixing.

Nitrogen, another nutrient important for algal growth, was also readily available for algae in 2020. Ammonia, nitrate, and nitrite are forms of nitrogen available to algae; at the surface all remained below the detection limit for much of the season. This indicates a significant amount of algal production is occurring in the lake. Lacustrine nitrogen measures were generally lower than riverine nitrogen, again suggesting tributaries are an important source of both nitrogen and phosphorus inputs. Hypolimnetic accumulation of ammonia was evident in summer and into early fall, stemming from the effect of thermal stratification over anoxic sediment. The anoxic conditions in the hypolimnion promote the release of ammonia from the sediments and decomposition of organic matter also contributes to increased ammonia concentrations. Because oxygen is not present, nitrification reactions do not occur; thus, the increase of hypolimnetic ammonia concentrations was both typical and expected. Upon fall turnover of the lake, oxygen was introduced which triggers nitrification, creating nitrite, which is readily further oxidized to nitrate. This phenomenon was observed September to October by a dramatic decrease in ammonia and measurable increase in nitrate concentrations. Data collected in 2020 and documented relationships in scientific literature demonstrate the connection from excess nutrients to degraded raw water quality, therefore it remains imperative to meet nutrient reduction targets outlined in the TMDL.

Nutrient and sediment load reduction targets were developed in the 2013 TMDL that, if met, would improve water quality in the lake such that designated beneficial uses can be attained. It suggests a 35% load reduction rate for Total Nitrogen, Total Phosphorus, and Suspended Solids.
This waste load allocation is divided amongst the three primary municipalities in the watershed: Moore, Norman, and Oklahoma City (ODEQ, 2013).

Chlorophyll-a is used as a proxy to measure algal biomass and it is important to understand the factors driving growth, due to its potential to cause drinking water and recreation issues. Lake Thunderbird’s SWS classification requires average chlorophyll to be less than 10 µg/L; however, lake wide chlorophyll concentrations in 2020 are over three times this number.

In 2020, average chlorophyll-a values increased from 2019 values, and remained excessive, representing a need to mitigate conditions driving increased algal biomass. Riverine sites experienced higher chlorophyll-a levels than lacustrine areas, but high turbidity likely limited algal growth and prevented even higher chlorophyll values. To control biological populations, it is important to understand what is driving their growth. In 2020, Walker’s (1999) analysis on non-algal turbidity was employed to look at light’s effect on algal growth. Results indicate non-native particles had a limiting effect on algal growth by minimizing the ability of light to penetrate the water column to drive productivity. Thunderbird’s TSI was examined using the most stable index, Chl-a TSI, and determined the lake ranged from oligotrophic in April to hypereutrophic by July, where it remained until November. During this same time frame, TN:TP ratios indicate the lake as indeterminate or co-limiting, suggesting factors other than nitrogen or phosphorus are driving productivity and algal growth.

Another consequence of cultural eutrophication that can lead to environmental problems is the proliferation of Harmful Algal Blooms (HABs). Several species of Cyanobacteria, or blue-green algae - a known contributor to HABs, occur in and dominate phytoplankton communities in many Oklahoma waters, including Lake Thunderbird. Taste and odor causing compounds such as Geosmin and MIB are released from blue-green algal cells following lysis, or senescence, and decomposition. The removal of elevated T&O compounds significantly increases the cost of producing palatable drinking water. The City of Norman has historically received T&O complaints in finished drinking water in September following significant lake mixing events. These mixing events contributed to T&O complaints through the process of hypolimnetically stored compounds mixing up and releasing into the epilimnion. Taste and odor complaints increased from 16 in 2019, to 28 in 2020. Geosmin peaked November while MIB in late August. Additional monitoring between October 2020-January 2021 indicated chlorophyll declined to near SWS criteria (10 µg/L). Aside from their causal relationship to T&O events, blue-green algae have the capability to produce multiple toxins that can cause skin irritations or lethality to humans, livestock, and pets that drink from untreated contaminated water sources.

Lake Thunderbird is on Oklahoma’s 2018 303(d) list of the Water Quality Integrated Report as impaired due to low dissolved oxygen, turbidity, and chlorophyll-a, with the driver of chlorophyll and dissolved oxygen impairments identified by the ODEQ TMDL as excess nitrogen and phosphorus.
Monitoring data collected in 2020 were added to the data set and analyzed for beneficial use impairments in accordance with the USAP (OAC 785:46-15) of the OWQS and Lake Thunderbird was found to be not supporting its Fish and Wildlife Propagation beneficial use due to turbidity. Additionally, Lake Thunderbird continues to exceed the 10 μg/L chlorophyll criterion for SWS and is thereby not supporting for its Public and Private Water Supply beneficial use. Nutrient and solids reductions are necessary for the lake to meet these water quality standards. Observed, continued eutrophication of Lake Thunderbird highlights the need for mitigation to meet impaired beneficial uses, as well as to improve and sustain suitability of a major drinking water source.

To improve water quality, dynamic in-lake and watershed level activities should be implemented in tandem and designed to facilitate effective, measurable mitigation in the future. Hypolimnetic oxidation is a worthwhile exercise to not only provide aerobic lake habitat, but also improve the quality of raw drinking water for municipalities and reduce recreational health risks due to the growth of harmful algae. Unfortunately, ongoing eutrophication indicates hypolimnetic oxygenation alone will not provide the relief Lake Thunderbird needs to recover its attainment of beneficial uses.

**Recommendations**

In past years, the monitoring strategy has been modified several times for a multitude of reasons, not the least of which is budgetary concerns. This has led to a somewhat disjointed monitoring plan that does not always address areas of concern. To that end, the water quality monitoring strategy was improved in 2020, at no cost to COMCD. The OWRB recommends those monitoring efforts be continued and expanded to include nutrients across all sites as they provided valuable information and minimize data gaps.

With the SDOX no longer operational, the COMCD should continue to explore and investigate other strategies or in-lake technologies to mitigate anoxic conditions in the hypolimnion. In 2021, the COMCD contracted an additional study to quantify the lake’s internal nutrient load. Such study can yield an important amount of information on existing/baseline conditions and additional sources of nutrients brought into the reservoir. Prior to this study, this information has only been estimated through sediment P concentrations. Results of internal loading should be included and considered to better understand a more accurate nutrient budget and could lead to improved management decisions and in selecting in-lake measures.

When watershed events continue to deliver non-point source pollutants above numeric targets and load allocations prescribed in a TMDL, the efficacy of in-lake measures may be diminished. Vigorous watershed BMP implementation is necessary to reduce nutrient and solids movement to waterways and into Lake Thunderbird where in-lake measures can further reduce pollutant
concentrations. Watershed level BMPs and in-lake mitigation strategies are not mutually exclusive and should be implemented in tandem. Elevated nutrients and low water transparency of the riverine sites underscore this need to meet TMDL reduction targets. General ways to accomplish this include:

- Incorporating wetlands into the landscape to ameliorate NPS pollutant runoff and sediment erosion further contributing to nutrient loads.
- Planning new vegetated swales and infiltration basins and retrofitting existing vegetated swales and infiltration basins.
- Target the retention of precipitation and runoff to reduce the impact of impervious surfaces in the watershed.
- Adopt Low Impact Development (LID) into COMCD’s practices for maintenance and construction.
- Encourage municipalities within the watershed to incorporate LID into any new construction within the watershed (Low Impact Development Center, 1999).
- Encouraging community involvement through outreach, education, Watershed Management Groups such as the Lake Thunderbird Watershed Alliance, grassroots neighborhood “Protect our Lake” groups, river cleanups etc.

Another avenue to improve Lake Thunderbird’s water quality health is to continue to foster cooperation and collaboration between all stakeholders – including municipalities and the recently formed Lake Thunderbird Watershed Alliance – to assist in reducing runoff from construction activities and urban land uses within the watershed. The COMCD continues to be an active leader in the management of Lake Thunderbird and initiate improvements to water quality.
References


OCC. (2010). Watershed Based Plan for the Lake Thunderbird Watershed. Oklahoma City, OK: OCC.


Appendix A
Quality Assurance and Quality Control Data

Water quality sampling followed the agency-specific Standard Operating Procedures (SOPs) (OWRB, 2017 and 2018). Several types of Quality Assurance/Quality Control (QA/QC) measures were employed to ensure quality data as part for the 2020 monitoring year, in the categories of collection, post-processing, and laboratory checks. These include:

- Timely review process of SOPs
- Calibration of field equipment
- Acid-washing and blanking Van Dorns before sample collection
- Sampler training and audits for field collection and sample processing
- Geographic site and depth verification to locate all sites
- Multiple stage review process for profile, field and lab data flowing to database
- Reviewing analytical lab data for flags and abnormal data
- QA/QC sample collection

QA/QC samples were collected in 2020 and included replicates and analytical blanks. Replicate samples primarily control for the collection of a representative sample, but these results also include a measure of uncertainty from laboratory analysis. Analytical blanks control for cleaning the equipment, such as the dissolved integrated samplers and Van Dorns.

Replicate samples were collected at the surface of the Site 1 for each parameter and designated as Site 1(12) and Site 1(22) for environmental and replicate samples respectively (Table 6).

<table>
<thead>
<tr>
<th>Date</th>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>4/13/2020</td>
<td>TKN</td>
<td>0.62</td>
<td>&lt;0.1</td>
<td>0.23</td>
<td>0.034</td>
<td>0.009</td>
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<td>&lt;0.1</td>
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<tr>
<td>6/8/2020</td>
<td>Ammonia</td>
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<td>&lt;0.1</td>
<td>&lt;0.05</td>
<td>0.038</td>
<td>&lt;0.005</td>
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<tr>
<td>7/13/2020</td>
<td>NO2/NO3</td>
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<td>&lt;0.05</td>
<td>0.037</td>
<td>&lt;0.005</td>
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<td>&lt;0.1</td>
<td>&lt;0.05</td>
<td>0.038</td>
<td>&lt;0.005</td>
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<td>&lt;0.005</td>
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<td>&lt;0.005</td>
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<td>0.062</td>
<td>&lt;0.005</td>
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<td>9/30/2020</td>
<td></td>
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<td>0.069</td>
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<td>NS</td>
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<td>NS</td>
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</tbody>
</table>

Table 6. Summary of 2020 Replicate Sample Results Designated as 1 (12) & 1 (22)
The relative percent difference (RPD) statistic is calculated to describe the precision of each laboratory parameter based on the comparison of replicate and duplicate sample pairs.

\[
\text{Eq. 6 } \text{RPD} = \frac{|x_{SI(12)} - x_{SI(22)}|}{\bar{x} (x_{SI(12)}, x_{SI(22)})} \times 100
\]

Equation 6 was applied to each replicate sample for each reported parameter. In Table 7, the acceptable precision limit for each parameter and the percent of sample events meeting that limit are listed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Acceptable precision for laboratory replicates</th>
<th>Number of Sample Events Meeting RPD Threshold</th>
<th>Percent of Sample Events Meeting RPD Threshold</th>
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<td>Total Kjeldahl Nitrogen</td>
<td>± 20%</td>
<td>10</td>
<td>100%</td>
</tr>
<tr>
<td>Nitrate/Nitrite</td>
<td>± 10%</td>
<td>10</td>
<td>100%</td>
</tr>
<tr>
<td>Ammonia</td>
<td>± 20%</td>
<td>10</td>
<td>100%</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>± 10%</td>
<td>7</td>
<td>70%</td>
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<tr>
<td>Ortho-Phosphorus</td>
<td>± 20%</td>
<td>10</td>
<td>100%</td>
</tr>
<tr>
<td>Chlorophyll-a, Sestonic Replicate</td>
<td>± 10%</td>
<td>11*</td>
<td>85%</td>
</tr>
</tbody>
</table>

*Chlorophyll-a sampled 13 times

Chlorophyll replicates met precision limits for the majority of the time but were still higher than other parameters. Chlorophyll is a biological parameter that is extracted under extreme care,
however, a high degree of variability in the chlorophyll pigment and other pigments between various algal species and individual algal cells is expected. Additionally, chlorophyll is analyzed using optical methods (i.e., spectrophotometric or fluorometric), which at times may over or underestimate chlorophyll concentrations due to the overlap of absorption and fluorescence bands of co-occurring pigments. Thus, it is not unexpected that a greater percentage of samples would not meet the RPD threshold for chlorophyll.
Appendix B

Temperature and Dissolved Oxygen with Depth

Temperature is denoted as Red Diamond Markers while Dissolved Oxygen is denoted as Blue Circle Markers.

Site 1 and 12 in April and May
Appendix C
Relative Thermal Resistance Plots

Site 1 4/13/20 Relative Thermal Resistance

Site 1 5/11/20 Relative Thermal Resistance